

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

MAY, 1954



MODERN PROCEDURES FOR
UNDERGROUND INVESTIGATIONS

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SOIL MECHANICS AND FOUNDATIONS
DIVISION

{Discussion open until September 1, 1954}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE \$0.50 PER COPY

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Reprints from this publication may be made on condition that the full title of paper, name of author, page reference (or page number), and date of publication by the Society are given.

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

MODERN PROCEDURES FOR UNDERGROUND INVESTIGATIONS

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Introduction

Late in 1951 a large manufacturing concern began construction of a four story addition to an existing mill. Since the mill had been in operation for fifty years without any sign of settlement, the designer of the addition paid little attention to foundations and merely stated on the plans that footings should be placed on firm soil. The contractor, to protect himself, made the time-honored plate load test on firm soil a few feet below the ground surface. This test indicated at least 4000 lb per sq ft bearing capacity, and so the footings were constructed on that basis. When only two stories of the addition were complete, two of the walls settled and cracked so badly that all construction was halted. A thorough foundation investigation was then made which disclosed that three corners of the building rested on hard soil and partially decomposed rock while the fourth was founded on a hard crust which was underlain by over 90 ft of soft, compressible silt.

This failure illustrates the need for investigating the underground conditions on even projects where everything appears favorable. The lack of correct information cost the owner a large sum of money for underpinning. Most of this could have been saved if the weak soil had been disclosed before construction. Fortunately, such failures are becoming less frequent. Both engineers and their clients are coming to realize that a little foresight is excellent insurance against subsequent trouble, and that money spent in underground investigations can save large repair bills later on.

In many cases, however, foundations investigations are conducted with little attention paid to proper planning or to utilizing modern techniques. A good example of such an investigation is the load test run by the contractor for the mill addition. He made a load test because such tests have been used for many years to determine soil bearing capacity. The results of this test contributed to the failure since they created a false confidence in the adequacy of the soil.

The development of a program for underground exploration which will prevent failure and which will furnish the designer with usable design data at a cost consistent with the value of the data is a challenging problem. It requires a sound knowledge of geology and soil mechanics; a feel for the practical problems of construction, and an understanding of the needs of the designer.

Developing the Program for an Investigation

Essential Underground Data

Before any investigation can be started, the engineer must decide what information about underground conditions is necessary. For example, on one

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project, the engineer's contract stated that the owner would furnish the data on the underground conditions. The owner, a shrewd business man, had borings made -- auger borings, which are the cheapest type. The engineer's soil data consisted of little jars of chopped-up, mixed-up samples which were little help in estimating the soil bearing capacity.

The soil information required depends on the type of structure involved. Table 1 summarizes the principal requirements of a complete investigation.

Table 1 - Essential Underground Data⁽¹⁾

1. Nature of the soil deposit (geology, recent history of excavation and filling, flooding, and the possibility of mineral exploitation)
2. Depth, thickness, and composition of each soil stratum.
3. The location of ground water.
4. Depth to rock and the composition of the rock.
5. The engineering properties of the soil and rock strata that affect the design of the structure.

Techniques and Costs

After the data requirements have been established, the proper techniques must be selected to provide the information at a minimum cost. During the past few years many new methods of exploration have been developed. Some of the new methods, like the use of heavy drilling mud, make it possible to secure good samples of soils which formerly could not be sampled at all. Others, such as the geophysical methods, enable the engineer to determine approximately the soil conditions over a large area at very low cost. The engineer must guard against the tendency of always using the same techniques, year after year, without taking advantage of the new developments. An engineer who boasts about using the same boring specifications for the past fifteen years would probably be ashamed to be driving a 1937 automobile this year; yet the advances in technology in both fields have been similar.

Any intelligent program must consider cost. Occasionally, more money is spent on exploration work than the value of the data justifies. In most cases, however, the small amount spent for exploration is saved many times by the reduced margin of safety required in design. For example, an investigation costing \$3000 made it possible to reduce the sizes of footings on a large office building by 25 per cent and reduce the footing costs by about \$12,000. Of course, when an investigation prevents failure, the savings can be much greater. Data collected by the writer on about 400 underground exploration projects indicate that the cost of an adequate investigation is roughly related to the total cost of a project. Typical relations are given in Table 2.

Table 2 - Cost of Underground Exploration

Buildings, Industrial Plants	0.03 % - 0.1 % of total cost
Dams	0.1 - 0.5
Highways	0.05 - 0.1
Bridges	0.1 - 0.2

Three-Step Program

The development of a logical sequence of operations is essential if the necessary information is to be secured without waste of time and money. In one

situation an industrial concern purchased a site, and then contracted for boring, sampling, and laboratory tests. The results of the investigation had some value since they indicated that the cost of foundations at the site far exceeded the value of the property. When the site was abandoned, much of the detailed soil data secured (and paid for) had served no purpose. The decision of whether or not the site was satisfactory could have been made with only a preliminary investigation costing little.

Any soil investigation can be resolved into three steps: Reconnaissance, exploration, and detailed examination. The reconnaissance step sizes up the situation, estimates the usability of a site, and indicates what exploration techniques will be most useful. Exploration determines exactly what the soil and rock conditions are at the site and provides preliminary data on the engineering problems involved. The detailed examination provides accurate engineering data on the critical strata disclosed by the exploration and is the basis for the final design.

Small projects coupled with simple soil conditions, may require only the first step. Large complex jobs will require all three. Since each investigation, large or small, proceeds from an extensive study to an intensive one, the engineer can stop the work when sufficient data are available without the accumulation of large amounts of useless information.

Reconnaissance

The reconnaissance investigation involves determining the nature of the soil deposit and estimating the soil and rock conditions. Since speed and low cost are primary considerations of this step, the engineer has to rely largely on existing data and on visual observation.

Data on many areas are to be found in geologic reports and in the surveys by agricultural soil scientists. Visual observation includes at least an examination of the site by a soils engineer or geologist, and the interviewing of nearby residents. Aerial observation and air photo analysis are recently developed techniques which are valuable in large scale reconnaissance.

A valuable supplement is a geophysical survey. Both the seismic (shock wave) and electrical resistivity methods have been used to estimate the depth to ground water and rock, and they have sometimes been successful in identifying rock and soil strata.

The reconnaissance data serves two purposes. First, it indicates whether the site is suitable for the structure and perhaps what foundation problems might be involved. Second, if the site is acceptable, it indicates which techniques may be necessary in conducting the second step of the investigation, exploration.

Exploration

The purpose of exploration is to determine accurately the depth, thickness, and nature of each soil and rock stratum, and the location of ground water. Although many different methods of exploration are in use, nearly all involve drilling holes in the ground and securing samples of the soils and rocks for identification and preliminary testing -- a procedure usually termed "test boring".

Boring Depth and Spacing

At the start of such work some decision must be made as to how many borings are to be made and how deep they should go. Unfortunately such a decision cannot be made intelligently until a few borings have been completed. The boring spacing depends on the uniformity of the soil deposit, and the nature of the structure. The following spacings are often used in making preliminary estimates:

Table 3 - Boring Spacing

<u>Project</u>	<u>Uniform, Stratified Soil</u>	<u>Average Soil</u>	<u>Erratic Soil</u>
Highway	1000 ft	500-1000 ft	100 ft
Earth Dam	200	100	25-50
Borrow Pits	500	200	50-100
Multi-story Buildings	100	50	25
One Story Buildings	200	100	25-50

Borings should extend deep enough to disclose all strata which could consolidate or shear under the load imposed by the structure. The depths given in Table 4 consider the weight and extent of the structure and are based on the stresses developed in the soil.

Table 4 - Depth for Exploratory Borings⁽¹⁾

<u>Building Width</u>	<u>Number of Floors (Typical Office Building)</u>				
	<u>1</u>	<u>2</u>	<u>4</u>	<u>8</u>	<u>16</u>
100 ft	11	20	33	53	79 ft
200	12	22	41	68	108
400	12	23	45	81	136

A simple rule often used by the writer is 10 ft of boring depth for each floor or its equivalent in loading.

Boring Methods

Test boring consists of two separate operations: Drilling, in which the different strata are uncovered; and sampling, in which suitable samples are secured for identifying the soils and for indicating roughly the soil's engineering properties.

Many different drilling methods are suitable so long as they do not disturb the soils appreciably and so long as they provide some means of recognizing changes in the strata. The characteristics of some widely used methods are given in Table 5.

Table 5 - Drilling Methods Suitable for Exploration

<u>Method</u>	<u>Applicability</u>	<u>Soil Disturbance</u>	<u>Recognition of Changes in Soil</u>
Hand Auger	All soils above ground water except gravels	Little	Excellent
Power Auger	All soils above ground water except coarse gravels	Little	Good to fair
Wash boring	All soils except gravels	Little(except dry sands)	Good
Rotary drilling	All soils except gravels	Little(except dry sands)	Fair(too fast)
Percussion well drilling	All soils	May be considerable	Fair
Coring with a tube	All soils except coarse gravels	Little except in sensitive or loose soils	Excellent if coring tube is short.

Deep drilling may require some method of preventing the bore hole from caving. Casing, used for many years, is satisfactory but expensive. Furthermore, it may cause considerable disturbance of loose cohesionless soils or sensitive clays. Drilling muds have been found very successful, since their pressure replaces that of the soil which had been removed. The only disadvantage is that they tend to obscure strata changes. Certainly neither method should be used if the hole remains open without help.

The requirements of the exploratory sampler are simplicity, and the ability to secure reasonably intact samples of many different soils. The most widely used are the split tube, thick-walled samplers which are driven into the soil with blows from a drop hammer. It is customary to measure the soil's penetration resistance during sampling by counting the number of hammer blows required to drive the sampler one foot. This is an indication of the soil's strength and density and a valuable aid to foundation design. Typical methods are given in Table 6.

Table 6 - Exploratory Sampling

<u>Sampler Type</u>	<u>Diameter</u>		<u>Hammer</u>	<u>Drop</u>	<u>Conversion Factor#</u>
	<u>Inside</u>	<u>Outside</u>			
Split spoon	1 in.	1.3 in.	140 lb	30 in.	1.5
Split spoon	1.4-1.5	2.0	140	30	1.0
Split spoon	2.0	2.5	300	18	1.0
Split spoon	2.5	3.0	375	18	1.0
Seamless	2.75	2.62	140	30	1.0

To convert penetration resistance to that of 1.4-1.5 in. ID Sampler

By far the most widely used in the United States is the 1.4-1.5 in. I. D. sampler driven with a 140 lb hammer falling 30 in. Considerable data and experience have been accumulated in terms of the penetration resistance measured by this combination; therefore its adoption as a standard is recommended.

Use of Exploratory Data

The major purpose of the exploratory work is to determine the depth, thickness, and nature of the soil strata. The detailed data from each boring are most effectively represented by a graph which shows the strata depths and thicknesses. Penetration resistances, the results of classification tests, and other pertinent data may also be shown graphically on the same record as shown in Fig. 1.

The over-all underground picture may be portrayed effectively by soil and rock profiles. These profiles are the basis for any subsequent analysis.

After the soil profiles have been developed an estimate may be made of the capabilities of the soils. This estimate is based on the penetration resistance and the results of simple soil tests such as liquid and plastic limits, water content, and grain size, but it is often sufficient for design purposes for small structures. From the results of over fifty detailed soil studies the writer has developed an approximate relation between soil type, penetration resistance and allowable footing pressure which is shown in Fig. 2.

The results of these estimates lead to one of three conclusions:

- (1) The soil conditions are so bad that further study will be of little value.
- (2) The soil conditions are so good that a reasonable design can be made on the basis of the exploratory data.
- (3) The soil conditions are probably satisfactory but additional detailed data are required before a safe or economical design can be made.

If the last conclusion is reached, the investigation proceeds to the last step--a detailed investigation of the critical strata disclosed by the exploratory work.

Detailed Investigation

The detailed investigation has as its objective accurate data on the engineering characteristics of the critical soil strata. This can be done either by undisturbed sampling and laboratory tests or by field tests on the soils in place in the ground.

Undisturbed Sampling

The art of undisturbed sampling has received considerable attention from soils engineers during the past fifteen years.⁽²⁾ The factors influencing sample disturbance have been identified, and many devices for sampling have been developed. The most important methods are given in Table 7.

Table 7 - Undisturbed Sampling Methods

<u>Sampler</u>	<u>Size</u>	<u>Method of Driving</u>	<u>Advantages</u>	<u>Disadvantages</u>
Thin walled tube	2-1/2-5 in.	Static force	Simple, low cost	Difficult to drive in hard soil. May obtain poor samples in very soft soils.
Thin walled with piston	2-1/2-5 in.	Static force	Few samples lost good in soft soils	Awkward to use
Rotary Double tube	2-1/2-6 in.	Static force and rotary cutting	Samples very hard soils	Expensive, May disturb soft soils

Hammering the sampler into the soil produces disturbance in soft or loose soils and should be avoided except where it is impossible to develop enough static pressure for sampling. In such soils it is doubtful that undisturbed samples are necessary.

Laboratory Testing

Sampling and testing are really a part of the same operation. They must be geared to each other so that the test results give a good picture of field conditions. The two most important considerations are minimum handling of the soil samples, and equipment and procedures which can be modified to fit the varying soil characteristics. Good testing is expensive and the cost of laboratory work on a large complete investigation may be 1/3 to 1/2 of the total.

In order to minimize the cost of testing it is often expedient to correlate test results with the results of simple, cheaper tests such as penetration resistance, water content, and the liquid and plastic limits. For example numerous studies have been made which relate unconfined compressive strength to penetration resistance.⁽³⁾ Table 8 summarizes the writers experiences with such relationships.

Table 8 - Relation of Penetration Resistance#, N, to Unconfined Compressive Strengths of Clays

Soil Type	Strength in 1000 psf		
	Min.	Avg.	Max.
Homogeneous highly plastic clays	.3 N	.5 N	.7 N
Medium plastic clays	.2 N	.3 N	.4 N
Very Low plasticity clays, plastic silts, clays with failure planes	.1 N	.15 N	.2 N

N is number of blows of 140 lb hammer falling 30 in. required to drive 1.5 in I. D. split spoon sampler one foot.

Field Testing

The ideal method would be to test the soils in place. The old-fashioned plate load test attempts just that, but its interpretation is often so nebulous that the results may be worthless. Recently cone penetration tests and rotating vane tests have been used to measure shear strength, but the disturbance produced by inserting the device appears to be as bad as that produced by sampling. It is likely, however, that more and better in-place test procedures will be devised, especially for testing easily disturbed soils.

Conducting an Investigation

A complete soil investigation consists of many complex operations which must be changed constantly to make them fit the conditions encountered. There are three principal ways that such investigations are conducted in the United States; each has its advantages and disadvantages, depending on the type of project and on the engineering organization which is doing the work.

The best method, of course, is for the designing organization to undertake the entire job of underground investigation. In that way each operation can be

best integrated with the larger problem of design of the structure. This requires that the designer maintain staffs of soil engineers, boring crews, and a complete soils laboratory. Except for a few very specialized phases of civil engineering work the only organizations which can afford such extensive staffs are the federal and state governments. Most private engineering firms do not have a sufficiently steady volume of the work to justify maintaining boring equipment and laboratories and so they turn to the other two methods.

The separate contract method involves dividing the soil investigation work into small units, usually the following; reconnaissance, geophysical exploration, boring and sampling, laboratory testing, and engineering analysis. Some larger firms are equipped to do some of these operations themselves, particularly the preliminary work and the engineering analysis, while a few even do their own laboratory testing. By breaking the work into such small units it may be possible to secure the best and cheapest job of each since there are many firms which specialize in these operations. However, there are two very serious objections to this method. First, there is a lack of good integration of the operations. Even though the entire job is supervised by one engineer, there is usually much lost motion since each independent contractor has his own methods of operation, and attempts to make him change or conform to some arbitrary procedure will result in poorer work at a higher price. The second difficulty is a lack of flexibility. In order to integrate all the separate steps it is necessary to prepare, ahead of time, rather rigid specifications for each. However, it is impossible to prepare specifications for underground exploration unless the underground conditions are known beforehand. If the conditions are known accurately enough to prepare specifications, it is doubtful if further exploration would be necessary.

The third method is a "package" investigation in which one firm that specializes in such work undertakes the entire job, from reconnaissance to analysis. This has the important advantage that each step of the work can be fitted into all the others with little lost motion. Furthermore, procedures can be changed as it becomes necessary without the need of writing new specifications or contracts. Good liaison with the designer is necessary of course, since the investigation organization is actually serving as a part of the design engineer's staff. The only disadvantage in this arrangement is that its success depends on the ability and integrity of the investigation firm. Of course, this is a disadvantage inherent in any job where a client hires an independent consultant, whether it is for soil exploration or the design of a structure.

All three methods are in use today, with the third or package method gaining in favor. The results in any case depend, to a large extent, on the understanding of the designer and the theoretical background, practical experience, and native ability of the soil engineer.

Summary

Soil investigations are an essential phase of the design of all civil engineering projects. They are exceedingly complex undertakings since they deal with a most complex subject, the earth itself. Careful planning is necessary in order to obtain the required data quickly and cheaply. The best investigation begins with an extensive study and ends with an intensive one. The first step, reconnaissance, estimates the soil conditions and determines if the site is usable. The second step, exploration, develops an accurate picture of the underground conditions and estimates the performance of structures on the site. The third step, a detailed investigation, secures accurate data on the engineering properties of the critical soil strata discovered in the second

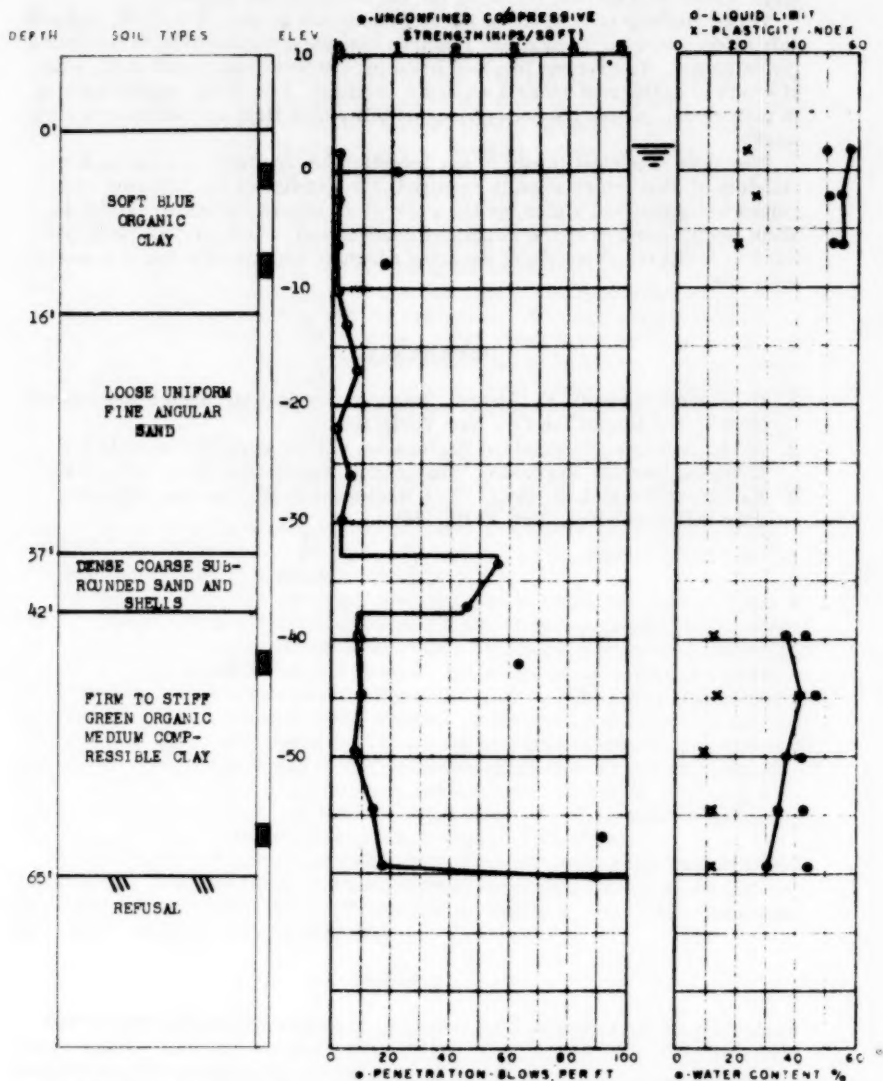
step. These data furnish the basis for the design of the project.

Three methods of conducting investigations are in use. The first, suitable only to very large organizations requires that the designer furnish the entire investigation. The second involves breaking the work into small units, each of which is performed under a separate contract. The third, rapidly gaining in momentum, places the entire responsibility on a firm specializing in such work.

The most important things in any investigation are first, a clear understanding of what information is required, a knowledge of the different techniques available, and a plan for the work which allows enough flexibility to adapt the procedures to the situations encountered. With all these it is possible to fulfill the objective of securing adequate data quickly and at a minimum cost.

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PENETRATION IS NUMBER OF BLOWS OF 140 LB HAMMER FALLING 30 IN TO DRIVE 1.5 IN SAMPLE TUBE 1 FT

UNDISTURBED SAMPLE

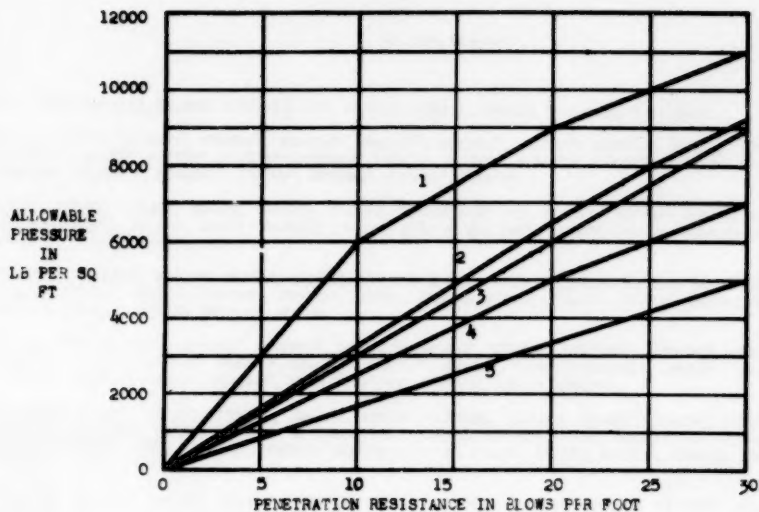
FIG 1--SOIL BORING RECORD SHEET

TEST BORING RECORD

BORING NO. 24

JOB NO. 370

LAW-BARROW-AGEE LABS INC
ATLANTA



- 1--Plastic silt, partially saturated clay.
- 2--Saturated clay, square footings.
- 3--Sands and gravels, dry.
- 4--Saturated clays, wall footings
- 5--Sands and gravels, flooded

FIG. 2--APPROXIMATE ALLOWABLE SOIL PRESSURE FOR FOOTINGS AS A FUNCTION OF PENETRATION RESISTANCE (THE NUMBER OF BLOWS OF A 140 LB HAMMER FALLING 30 IN. REQUIRED TO DRIVE A 1 1/2 IN. I.D. SPLIT SPOON SAMPLER ONE FOOT)



Figure 1. Effect of initial concentration on the rate of adsorption of lead ions by activated carbon. The conditions were: temperature, 25°C; pH, 5.0; adsorbent dose, 0.5 g/L; and shaking time, 120 min.

The results of the adsorption of lead ions by activated carbon are shown in Figure 1. The adsorption capacity of activated carbon for lead ions was found to be 1.5 g/g at an initial concentration of 1.5 g/L. The adsorption capacity of activated carbon for lead ions was found to be 1.0 g/g at an initial concentration of 1.0 g/L. The adsorption capacity of activated carbon for lead ions was found to be 0.5 g/g at an initial concentration of 0.5 g/L. The adsorption capacity of activated carbon for lead ions was found to be 0.0 g/g at an initial concentration of 0.0 g/L.

0

Figure 2. Effect of initial concentration on the rate of adsorption of lead ions by activated carbon. The conditions were: temperature, 25°C; pH, 5.0; adsorbent dose, 0.5 g/L; and shaking time, 120 min.

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MAY: 435(SM), 436(CP)^e, 437(HY)^e, 438(HY), 439(HY), 440(ST), 441(ST), 442(SA), 443(SA).

a. Beginning with "Proceedings-Separate No. 200," published in July, 1953, the papers were printed by the photo-offset method.

b. Presented at the Miami Beach (Fla.) Convention of the Society in June, 1953.

c. Presented at the New York (N.Y.) Convention of the Society in October, 1953.

d. Beginning with "Proceedings-Separate No. 290," published in October, 1953, an automatic distribution of papers was inaugurated, as outlined in "Civil Engineering," June, 1953, page 66.

e. Discussion of several papers, grouped by divisions.

f. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.

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